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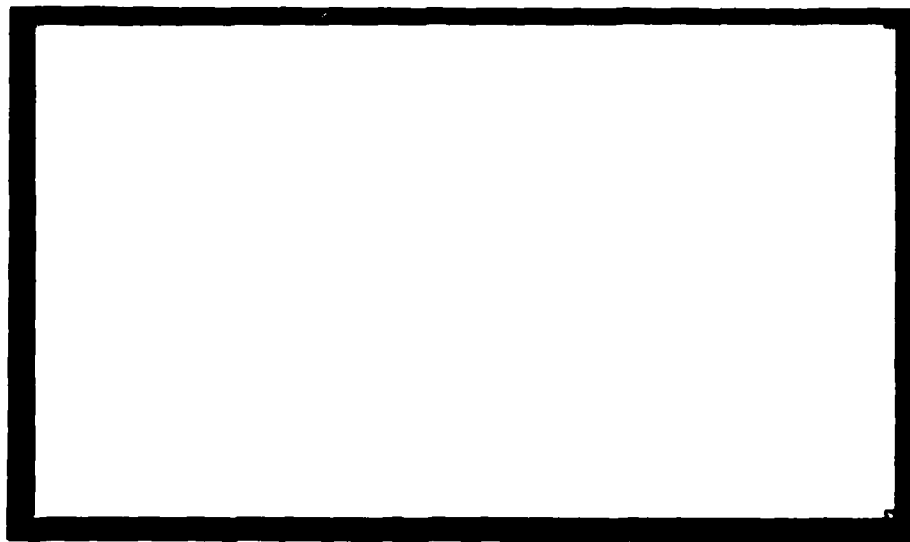
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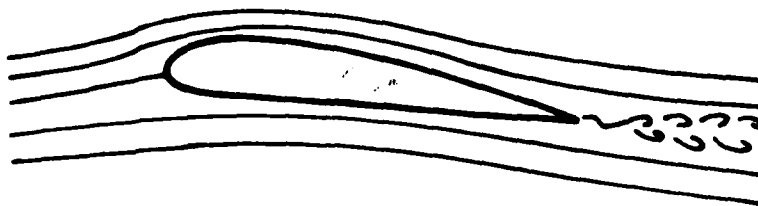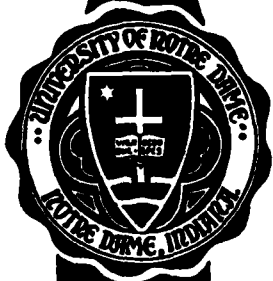
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Aerodynamics Laboratory

**Department of Aerospace
and Mechanical Engineering**

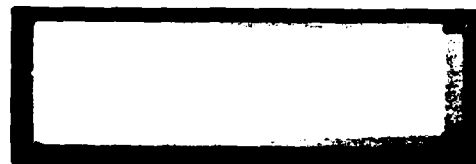## University of Notre Dame
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Three problems which have been investigated are discussed in this report. Aerodynamic theory and computational procedures have been developed to study the aeroelastic stability of oscillating loaded airfoils in cascade with interblade phase angle. Contrary to linear theory, results show that classical flutter can occur for low speed turbine cascades operating at typical design conditions. Ground effects on fan inlet flows were investigated based on data from NASA – Lewis. The analysis showed that swirling flows are the dominant source of flow disturbances entering the fan.

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Finally, a study was made of three-dimensional periodic disturbances acting upon loaded airfoils in cascade.

FINAL REPORT

TO THE

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

ON CONTRACT NO. F49620-79-C-0014 ENTITLED

AERODYNAMICS OF CASCADED AIRFOILS OSCILLATING OR SUBJECT

TO THREE-DIMENSIONAL PERIODIC GUSTS

FOR THE PERIOD OF OCTOBER 1, 1978 TO DECEMBER 31, 1980

BY

H. ATASSI

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I. INTRODUCTION

The present research is motivated by the ongoing technological developments in turbomachine blading systems. The new designs tend toward increased thrust per unit engine weight and more stable operating conditions. The performance of the engine is greatly enhanced by higher blade loading and increased flow speed. This creates many new problems in fluid mechanics, aerodynamics, and aeroelasticity. For example, the higher blade loading produces new flow patterns in the wakes. These irregular flow patterns interact with structural elements such as rotors and guide vanes and induce fluctuating aerodynamic forces on their blades. The aeroelastic stability of the engine, therefore, depends on the interaction between the fluid mechanics, the aerodynamics, and the structural dynamics of the blading systems.

The main objective of our research was to focus on the unsteady aerodynamics and the aeroelastic stability of loaded airfoils in oscillatory motion or subject to nonuniform flows. However, during the main course of our work, we also have encountered some interesting problems related to the nature of the flow entering the inlet of a turbofan engine. Inlet flow patterns are the initial flow conditions for any aerodynamic analysis. Accordingly, we have extended our research objectives to also investigate ground effects on jets and fan inlet flows.

Three sets of problems have been investigated:

(1) First, we studied the unsteady aerodynamics and the aeroelastic stability of oscillating loaded airfoils in cascade with interblade phase angle. The aerodynamic theory and computational procedures have been developed. A general computer code for arbitrary airfoil and cascade geometry evolved from the analysis and was applied to investigate flutter conditions for compressor-like and turbine-like cascades. The results show that classical flutter can occur for low speed turbine cascades operating at typical design conditions. A significant result since linear theory shows no flutter.

(2) Second, we investigated ground effects on jet and
     fan inlet flows. Our investigation was based on
     data obtained at NASA Lewis Research Center. We
     first developed an analytical model for the mean
     flow. An experiment was also undertaken to check
     the theoretical model. We then modeled the pattern
     of disturbances entering the fan inlet. The results
     show that swirling flows are the dominant source of
     flow disturbances entering the fan.

(3) The third problem we anlyzed was that of
     three-dimensional periodic disturbances acting upon
     loaded airfoils in cascade. The three dimensional
     character of the disturbance results from the
     complex irregular flow pattern behind rotors or
     guide vanes. It may also result from entering
     swirling flows due to ground effects or atmospheric
     turbulence. In the case of a linear cascade the
     mathematical formulation leads to a single Helmholtz
     equation. The theory was first applied to symmetric
     airfoils.

II. AERODYNAMIC AND AEROELASTIC CHARACTERISTICS OF OSCILLATING LOADED CASCADES

At subsonic speed aeroelastic instabilities of turbomachine blading

systems are generally attributed to stall flutter [1,2]. This type of flutter

strongly depends on the separated flow condition during at least part of each

cycle of oscillation. The accurate analysis of stall flutter is still elusive

and one has to rely on semi-empirical methods for predicting its condition.

Classical flutter, on the other hand, assumes the flow to be potential

around the body. It is generally not considered as a cause of flutter at low

speed because one tends to associate the operation of rotating turbomachinery

with high speed and high angle of attack where flow separation occurs. Recent

blade design however, has greatly improved, and measurements by Kirschner et

al. [3], and Carta [4] at United Technologies Research Center indicate flutter

instabilities occuring with attached flows. The speculation was that at high

blade loading, classical flutter may occur.

Linear aerodynamic theories and aeroelastic analyses yield unstable conditions only at very low reduced frequency. This usually corresponds to larger critical flutter speeds than deemed acceptable for the validity of the analysis. These linear aerodynamic theories assume the blades to be flat plates at zero-incidence to the mean flow and thus exclude any coupling between the mean potential flow and the unsteady flow disturbances.

This created a definite need for the development of an aerodynamic theory for highly loaded airfoils in cascade. Such a theory will yield the aerodynamic forces and moments to be used in an accurate aeroelastic analysis of highly loaded blades.

1. Aerodynamic Theory and Computational Procedure

We have developed a complete theory for the analysis of oscillating airfoils in cascade in uniform incompressible flows. The theory fully accounts for the geometry of the airfoils and cascade parameters. The coupling between the mean flow of the cascade and the unsteady field resulting from its oscillation is completely included in the analysis. The effects of the strong mean velocity gradient near the leading edge is also included. Our formulation is rigorous and complete. A schematic of the problem is shown in Fig. 1.

The unsteady velocity field is formulated in terms of two singular integral equations defined along the contour of the airfoils. An important particular solution is derived in a closed analytical form. This solution represents the effect of the velocity gradient of the mean flow on the unsteady flowfield. Finding this solution was a breakthrough in our analysis and enabled us to regularize the density function in the integral equations. We also note that the present theory uses hypercomplex functions, a feature that in addition to its mathematical elegance contributes to simplifying the

analaysis. Details are given in [5,6].

The computational procedure solves the two integral equations by collocation. A special attention is paid to evaluate the Cauchy integrals between two collocation points.

2. Unsteady Pressure Distribution on Oscillating Airfoils in Cascade

A study of the unsteady pressure distribution along the airfoils surface was carried for six cascades (see Table 1, for cascade parameters) and for different values of the reduced frequency. The results are given in [6]. Figures 2, 3, 4, and 5 give the real and imaginary components of the unsteady pressure distribution for plunging and rotational oscillations for cascade C5. The reduced frequency k is varied from 0.1 to 5. It is noted that no simple pattern exists for the two pressure components (one is in-phase with the velocity, the other is out-of-phase) as in the case of flat-plate cascades. At low reduced frequency the pressure pattern is dominated by its shape near the leading edge. The center of pressure is forward of the airfoil center. However, as k increases, the value of the pressure increases along the airfoil surface and the relative importance of the leading edge is reduced.

It is also remarkable to note that for both plunging and rotational oscillations, the pressure component in-phase with the oscilltory velocity is only slightly affected by the stagger of the cascade and the interblade phase angle of the oscillatory motion.

Finally, a special investigation of the unsteady pressure and its gradients near the leading edge was also carried out because they play an important role in the formation of the leading edge separation phenomena. Results are given in [6].

3. Unsteady Forces on Compressor and Turbine Blades

The unsteady lift forces acting upon various cascade blades were investigated for both plunging and torsional oscillations. Results are reported in [6,7,8]. Comparison with previous treatments which neglect the strong coupling between the mean flow and the unsteady aerodynamic field, shows significant difference in phase and magnitude of the aerodynamic forces.

As an illustration, Fig. 6 shows the unsteady moment for cascades C1 to C6 in rotational oscillations. The reduced frequency is varied from 0 to 1. The significant effect of loading and thickness are well shown for the case of C5 where the aerodynamic damping is negative up to a reduced frequency of 0.5. This indicates the possibility of flutter for a flow Mach number larger than 0.5.

This raises the possibility of classical flutter occuring due to high loading effects in compressors operating at typical design conditions. Previously, flutter at subsonic Mach number was always attributed to stalling flow conditions on the airfoils.

4. Stability Analysis and Flutter Boundaries

Because of the possibility of classical flutter – flutter in a potential flow resulting from coupling between bending and torsional modes, occuring due to high blade loading, we have undertaken a complete study of stability analysis for compressor-like and turbine-like cascades. Detailed results are given in [7,8,9].

First in [7], we carried out a comparative study for a compressor, a turbine, a flat plate cascade, and a single airfoil having the same blade geometry. Table 2 gives the parameters for the cases studied. The schematic of the physical problem is shown in Fig. 7. For moderate blade thickness, instability is absent in pure bending except for turbine at very low frequency. For pure torsional oscillations, Figure 8 shows that instabilities

occur only at low reduced frequencies below 0.20 for the turbine cascade. However, for a compressor cascade it is significant to note that it is unstable up to a reduced frequency of about 0.7.

Second, we carried out studies for combined bending and torsional oscillations for different stiffness ratios. The coupling of bending and torsion results in flutter speeds that are lower than those of pure torsion at certain stiffness ratios. In particular, Fig. 9 shows that for a typical stiffness ratio, $K = 0.5$, higher bending modes than the first coupled with the first torsion mode can result in flutter at low speeds at typical torsion axis locations.

Our cooperation with researchers from Brown, Boveri, and Company (BBC) led us to exchange some of our results. BBC experiments showed flutter for their turbine blades at operating conditions. They provided us with the cascade and blade geometry shown in Fig. 10. The parameters and operating conditions are given in Table 3. Our analysis shows the existance of high frequency pockets of instabilities for coupled bending and torsion. Typical instability and flutter boundaries are shown in Figs. 11 and 12. The engineering relevance of the results however necessitates the inclusion of structural damping in our analysis. As a result, when a 0.01 of structural damping was introduced in the analysis, the high frequency pockets of instabilities disappeared. However for typical stiffness ratio of 0.5 the flutter boundaries show that flutter can occur at typical operating conditions. Details are given in [8,9].

In conclusion, our analysis shows that classical flutter can occur for highly loaded low speed cascades operating at typical design conditions. Aeroelastic analysis based on linear aerodynamic theories which neglect the coupling between the mean potential flow and the unsteady disturbances do not properly predict flutter condition for thick highly loaded blades.

III. EFFECT OF SHAPE AND INCIDENCE ON THE STABILITY OF A SINGLE AIRFOIL IN PITCHING OSCILLATIONS

In II we reported on our studies of the aerodynamics and the aeroelastic properties of vibrating cascades. It is interesting from the academic point of view as well as the engineering application to perform similar analyses for a single airfoil. Hence, we carried out an investigation of stability and flutter boundaries for a single airfoil having small pitching oscillations in a low-speed flow. The analysis reveals that the airfoil camber and thickness significantly shift the stability and flutter bounds toward higher reduced frequencies and lower flutter speeds than for a flat plate airfoil. A region of instability is also found for airfoils hinged aft midchord at a reduced frequency of about unity. For an airfoil hinged at the leading edge, the airfoil camber and thickness are destabilizing and strongly reduce the limiting values of the inertial parameter at which flutter is possible. Details are given in [10].

IV. GROUND-INDUCED EFFECTS ON JET AND FAN INLETS

Distorted flow into jet and fan engine inlets has been shown to have deleterious effects on engine performance by causing stall and surge in such devices, amplification of acoustic response, and inducing blade vibrations. In particular, during take-off and landing of jet powered aircraft the presence of a ground plane is responsible for the formation of a vortex which is convected into the inlet causing distortion of the inlet flow. Figure 13 which was taken at NASA Lewis Research Center clearly shows the existence of a vortex line extending from a stagnation point on the ground and entering the engine inlet.

Because inlet flow distortion produces vorticity waves on the fan blades, we have developed a free-streamline potential flow model for the flowfield external to a stationary jet inlet in proximity to the ground. The model is

shown schematically in Fig. 14. The model accounts fo. .low separation at the lips and avoids singularities by assuming the development of free-steamlines at the inlet lips. Solutions are obtained in closed forms for the two-dimensional model except for solving two simple algebraic equations.

The results show strong dependence of the flow pattern on the diameter-to-height ratio, $\alpha = D/H$. Three flow regions are found:

(i) $0 < \alpha < 1.08$,

with two different distinct solutions.

(ii) $1.08 < \alpha < 1.59$,

with two similar distinct solutions.

(iii) $\alpha > 1.59$,

with no solution.

This is a remarkable result which we can not explain at the present time. However, the position of the stagnation point on the ground predicted by our simple model (Figure 15) is within 3% of the one measured at NASA Lewis and shown in Fig. 13. Both correspond to $\alpha = 0.3$.

A water table experiment was undertaken to also check the results of our model. Figure 16 shows a colour picture of the flow for $\alpha = 0.3$ which gives excellent agreement with the theory as to the shape and position of the stagnation point. Figure 17 shows the flow for $\alpha = 2$, for which no analytical solution exists. A recirculating flow region appears in the flow and may explain the non-existance of the potential flow solution.

Finally, convective three-dimensional disturbances were added to the model to study their evolution as they enter the fan inlet. The results show strong dependence on initial vortex formation and location. They also show that small disturbances are greatly amplified at the inlet plane due to the

flow turning and acceleration, and hence may produce a relatively unstable swirling flow. Such magnification of initially small disturbances of course invalidates the linearization process used in the analysis. The importance of nonlinear effects is yet another question that needs further investigation. Details are given in [11,12,13].

V.   THREE-DIMENSIONAL CONVECTED GUSTS INTERACTING WITH LOADED BLADES

Unsteady airfoil theory has been mainly developed in the linearized approximation wherein the blades are assumed to be flat plates at zero incidence to the mean flow. In this approximation the treatment of the gust problem can be readily reduced to that of an oscillating flat plate or cascade of flat plates with the proper boundary conditions. The incident vortical gust wave is not disturbed in the linear case and provides the values of the upwash along the airfoil surface.

For highly loaded blades with large air turning, the incident vortical wave is distorted as shown by Goldstein and Atassi [14]. For a two-dimensional gust, however, the magnitude of the vorticity is conserved as it is carried by the mean potential flow. But for a three-dimensional gust both magnitude and wave length vary considerably as they interact with the mean flow.

The objective of this part of our research is first to properly formulate the mathematical theory for a three-dimensional gust interacting with loaded airfoil and then to develop the computational procedure to solve the mathematical equations.

First it is essential to show the three-dimensioal character of the gust in turbomachinery. Figure 18 shows a schematic of the nonuniform pattern of the flow behind a rotor stage. Secondary flows, viscous wakes, and tip and hub vortices tend to create a very complex flow pattern. As this nonuniform

flow pattern moves with respect to a subsequent row downstream, a gust wave is generated as shown in Fig. 19.

We have formulated the mathematics of this problem in terms of a single Helmholtz equation even for a three-dimensional gust. Details about the mathematical formulation are given in [15]. Preliminary results for a symmetrical airfoil and cascade were obtained and show significant effects for the resulting aerodynamic forces acting on the blades. The general problem for loaded airfoils are still in the formulation stage. Certain difficulties occur because of the singular behavior of the streamwise vorticity component along the blade surface. We are pursuing the mathematical and computational investigation of this problem and hope to have definite results in the near future.

VI. FUTURE PLANS

Our future plans are influenced by the progress being made in the unsteady aerodynamics of turbomachine systems, and of course by our co-operation with other researchers and engineers in the field. Essentially these are the problems we shall be pursuing and developing in the near future.

1. Three-Dimensional Vortical Disturbances Acting Upon Loaded Airfoils

As we mentioned earlier this problem is of great practical importance to the stability of turbomachine blades. Its applications, however, extends to many other engineering systems such as propellers, helicopter blades, noise, etc. It is a new and challenging problem and requires the development of new analytical and numerical tools for its solution.

2. Stability Analysis of Vibrating Cascade Blades With Amplitude Modulation

Recent experimental data reveals amplitude modulation of vibrating blades in addition to interblade phase difference. No analysis has ever been carried out of such a problem. We believe our theory for the oscillating cascade

blades could be extended to account for amplitude modulation. This problem was brought to our attention while visiting Whittle Laboratory, in Cambridge, England.

3. Unsteady Flows Near Leading and Trailing Edges

Certain difficulties occur in numerical computation when we deal with a sharp leading edge, or a non cusped trailing edge. These problems have to be dealth with through expansion of the analytical solution in these areas. Otherwise, they introduce significant errors in the final results. We did carry out an analytical study for the case of the vibrating cascade in incompressible flow. However, we know that some other researchers with purely numerical schemes have experienced certain diffulties and they are not yet resolved. We feel this is a problem which should first receive analytical treatment and we plan on investigating its effects for arbitrary values of the Mach number.

4. Compressibility Effects

Our stability analysis of oscillating airfoils and cascades shows that thickness and loading could be very destabilizing. It is argued that incompressible analysis leads to conservative flutter bounds, and that compressibility effects tend to further destabilize the system. There is no simple answer to this problem at the present time. We feel there is need for a relatively simple analysis to indicate the effects of high Mach number, particularly at low and large reduced frequencies.

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FIGURE SYMBOLS AND PARAMETERS FOR CASCADES STUDIED

Cascade	Symbol	% Thickness	Camber Angle	α (deg.)	δ (deg.)
C_1	O	5	0	0	0
C_2	△	11.25	0	0	0
C_3	□	11.25	32	0	0
C_4	◇	11.25	32	16	0
C_5	▽	11.25	32	16	37.5
C_6	■	11.25	32	0	37.5
C_7	▲	11.25	0	0	37.5
C_8	●	5	0	0	37.5
C_9	⬣	0	0	0	37.5
Isolated Flat Plate	⬡	0	0	0	-

Table 1

	Compressor	Turbine	Single Airfoil
Steady Load	0.76	1.48	2.79
Flow Deflection (deg)	23.76	25.92	0
Discharge Velocity	0.68	1.38	1.0
Stagger (deg)	37.5	-37.5	--
Interblade Phase Angle (deg)	54.0	306.0	--

Thickness = 11.25% of chord, Camber angle = 31.64 deg

Angle of attack = 16.0 deg., Cascade solidity = 1.01

Table 2. Parameters of Cascades Studied for
Comparison of Compressor, Turbine,
and Single Airfoil Effects.

GEOMETRY AND OPERATING CONDITIONS

OF THE CASCADES

Thickness Ratio	0.30
Camber ratio	0.25
Angle of Attack α_o	28.71^o
Stagger Angle δ	-28.71^o
Solidity	1.22
r_c	0.468
m	2000
Steady Load	4.38
Flow Turning	61.0^o
Pressure Loss $(P_\infty - P)/(\rho U_\infty^2)$	1.63

Table 3. Geometry and Operating Conditions for the Brown Boveri Cascade.
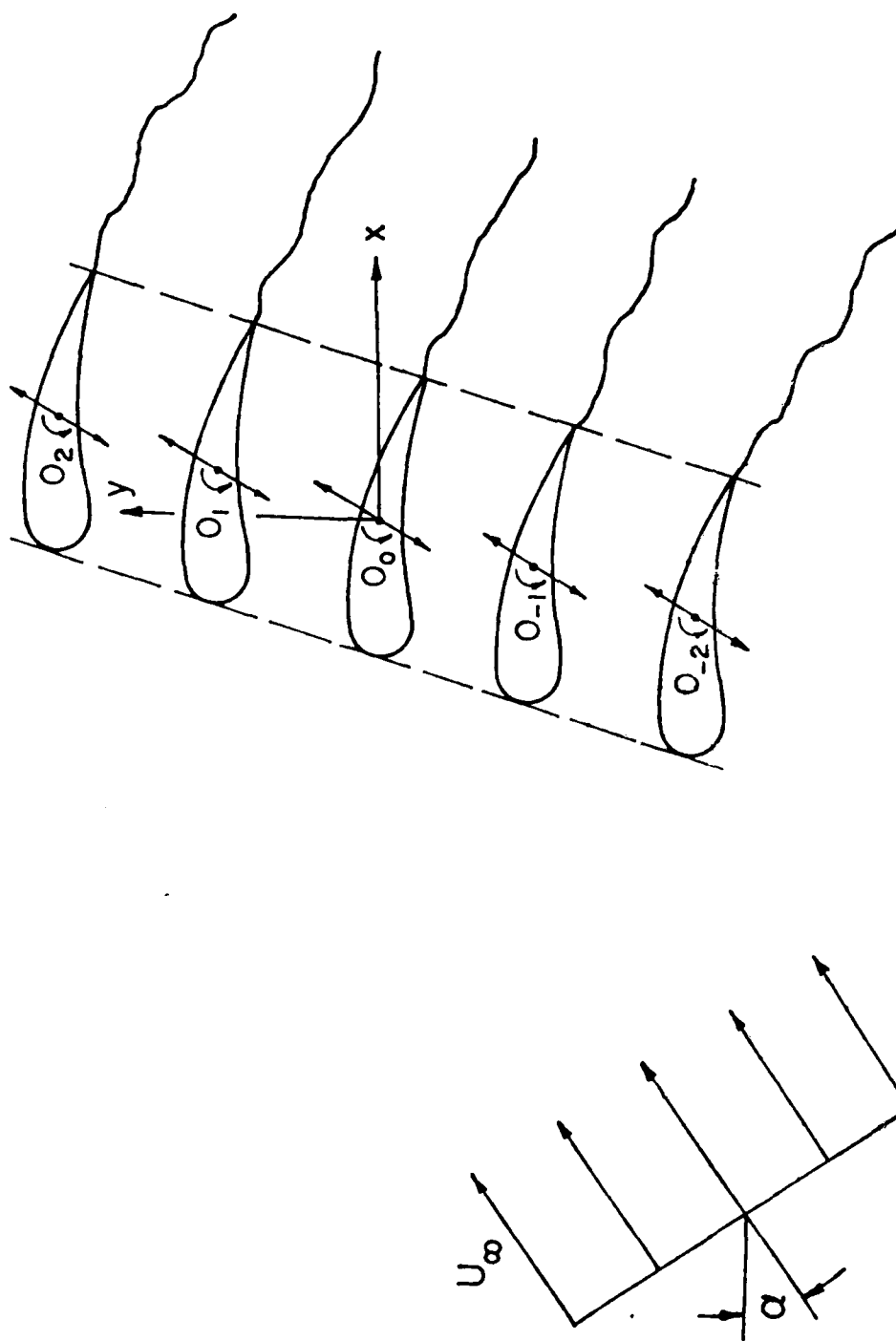
Figure 1.   SCHEMATIC OF THE OSCILLATING CASCADE PROBLEM.
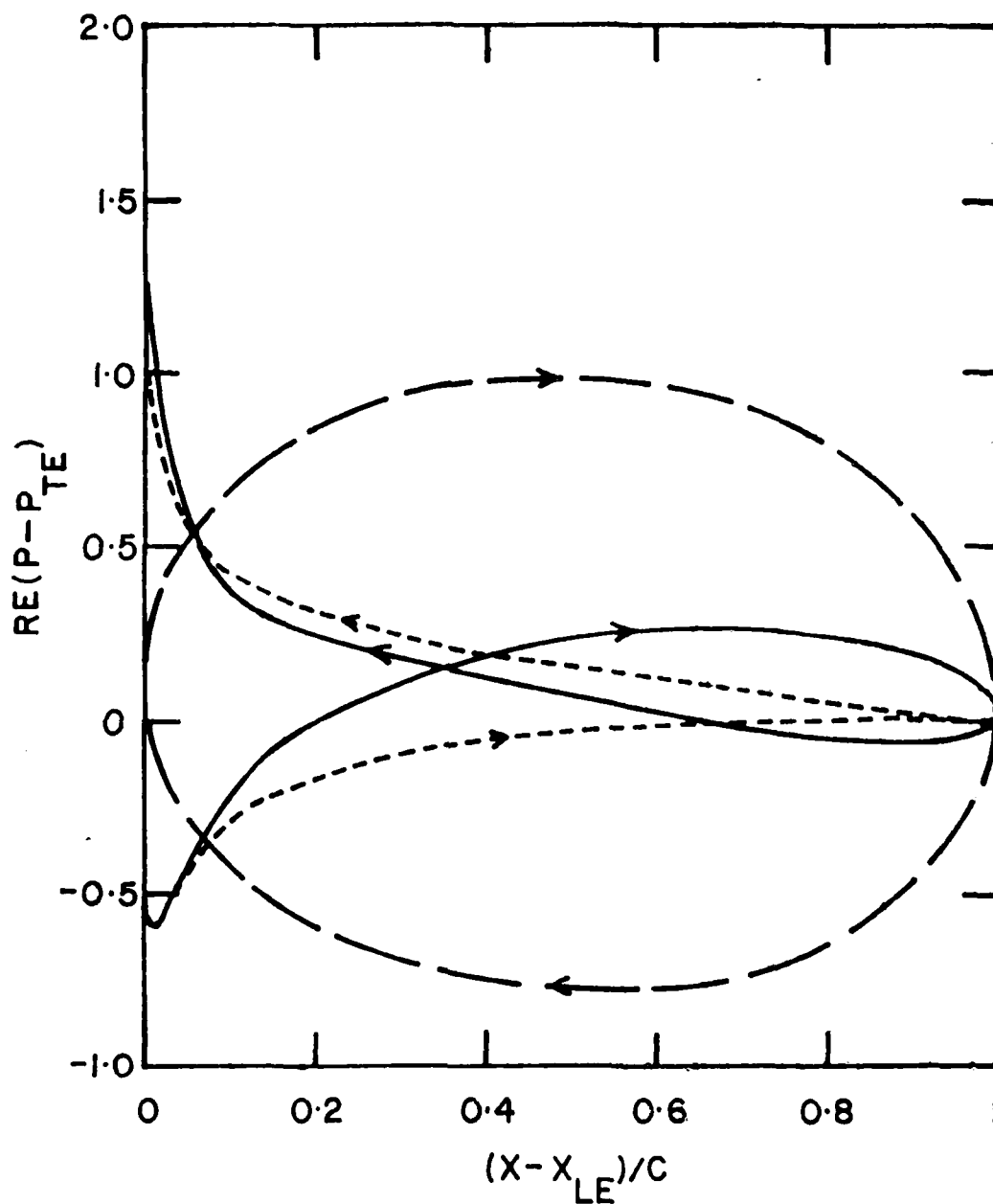
Figure 2. Real component of the unsteady pressure distribution for plunging oscillation. Cascade C_5; ---, $k = 0.5$; − −, $k = 3.0$. For $k = 3$, the scale of the ordinate is reduced by a factor of 10. C_5: $t = 11.25$, $\beta = 32^O$, $\alpha = 16^O$, $\delta = 37.5^O$, $\sigma = 90^O$.
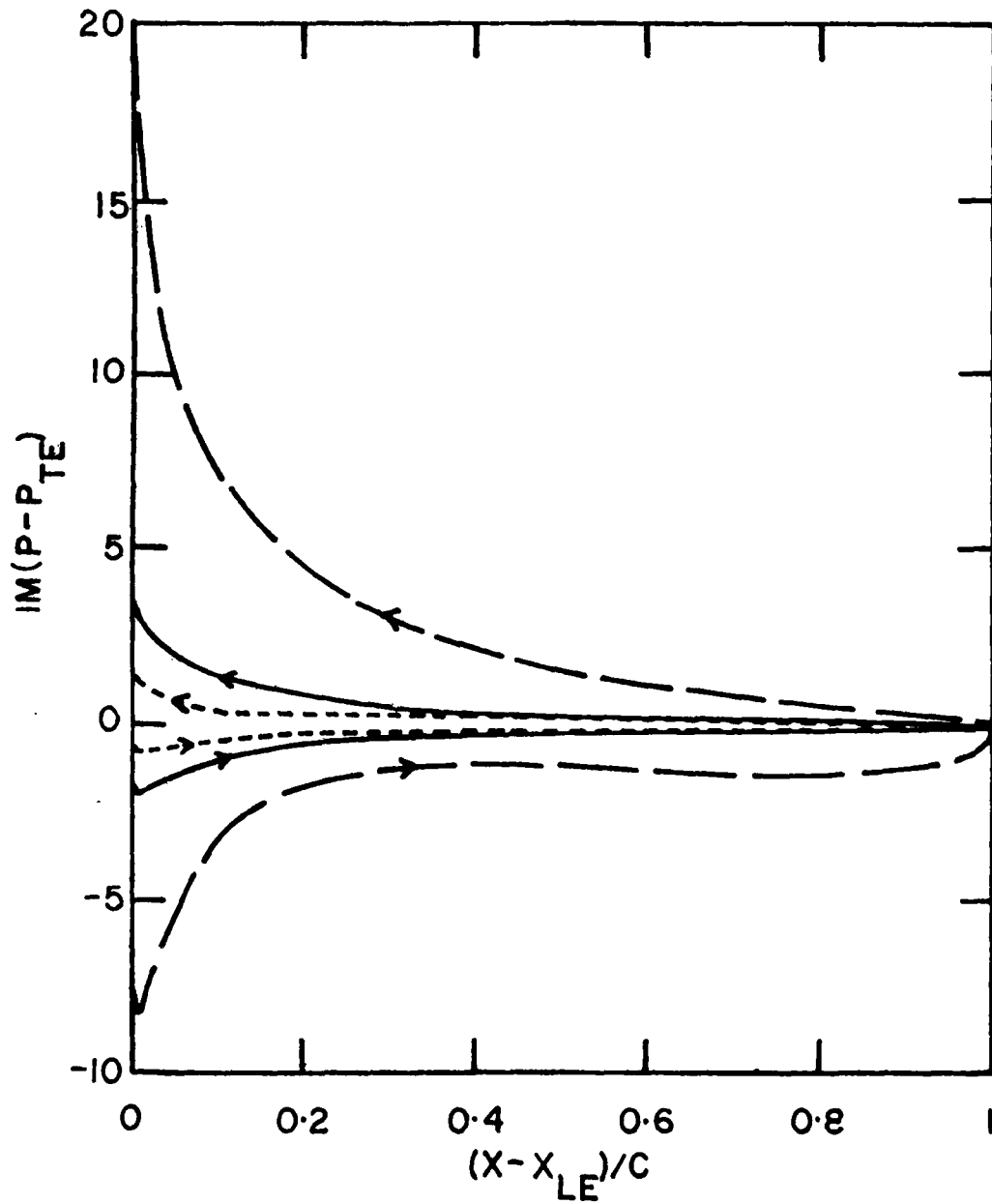
Figure 3. Imaginary component of the unsteady pressure distribution for plunging oscillation. Cascade C_5; ---, $k = 0.1$; —, $k = 0.5$; – –, $k = 3.0$. C_5: $t = 11.25$, $\beta = 32^O$, $\alpha = 16^O$, $\delta = 37.5^O$, $\sigma = 90^O$.
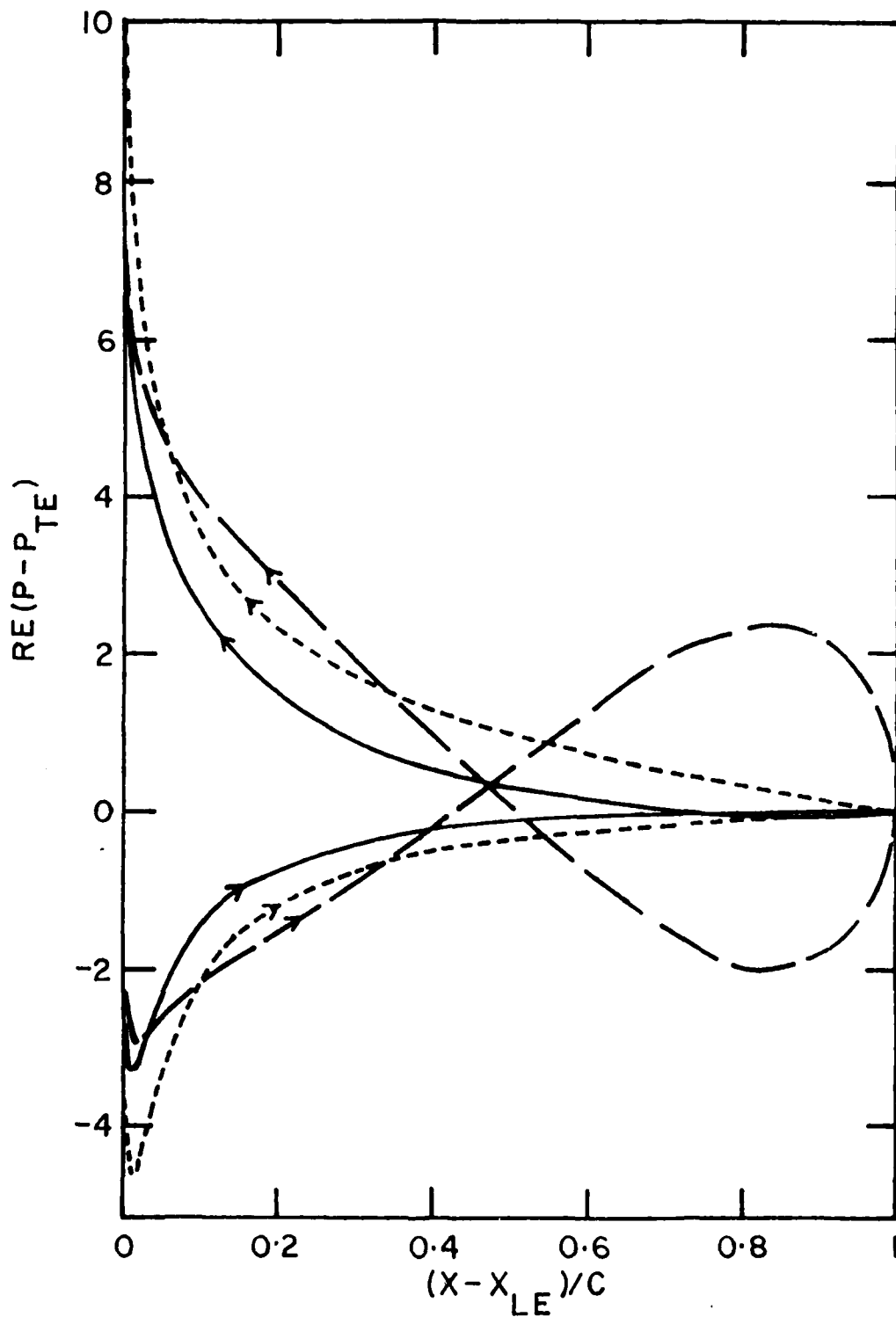
Figure 4. Real component of the unsteady pressure distribution for rotational oscillation. Cascade C_5; ---, $k = 0.1$; —, $k = 0.5$; — —, $k = 3.0$. C_5: $t = 11.25$, $\beta = 32^O$, $\alpha = 16^O$, $\delta = 37.5^O$, $\sigma = 90^O$.
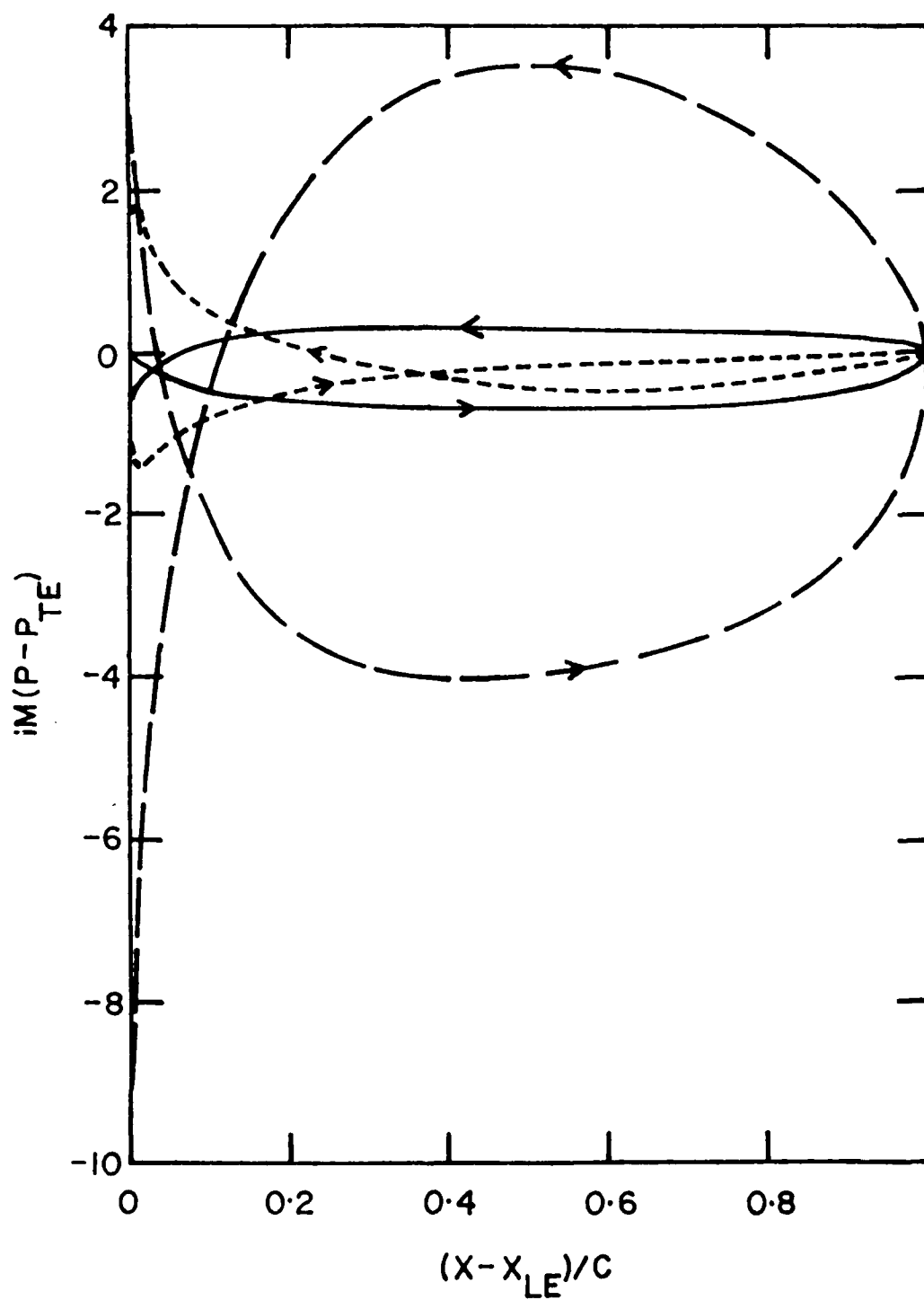
Figure 5.   Imaginary component of the unsteady pressure distribution
for rotational oscillation. Cascade C_5;---, k=0.1; —, k=0.5;
— —, k=3.0. C_5: t=11.25, β=32°, α=16°, δ=37.5^O, σ=90°.
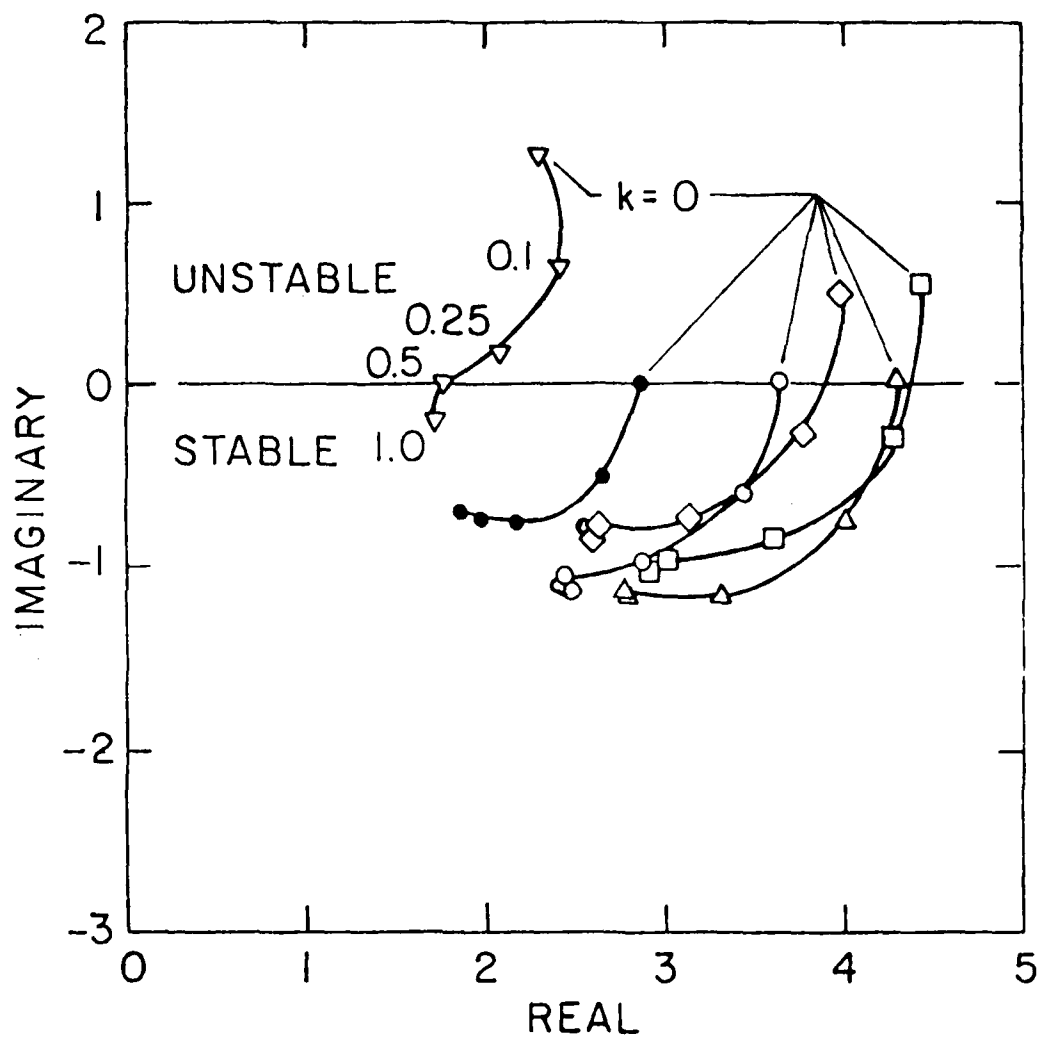
iqure 6.   Unsteady moment for cascades C_1 to C_6 in rotational oscillation. The reduced frequency is varied from 0 to 1. C_1, O; C_2, Δ; C_3, □: C_4, ◇: C_5, ∇: C_6, ●. C_1: t=5, C_2-C_6: t=11.25: C_1-C_2: ß=0°, C_3-C_6: ß=32°: C_1-C_3: α=0°, C_4-C_6: α=16°: C_1-C_4: δ=0°, C_{5-6}: δ=37.5°: C_1-C_5: ʋ=90°, C_6: ʋ=180°.
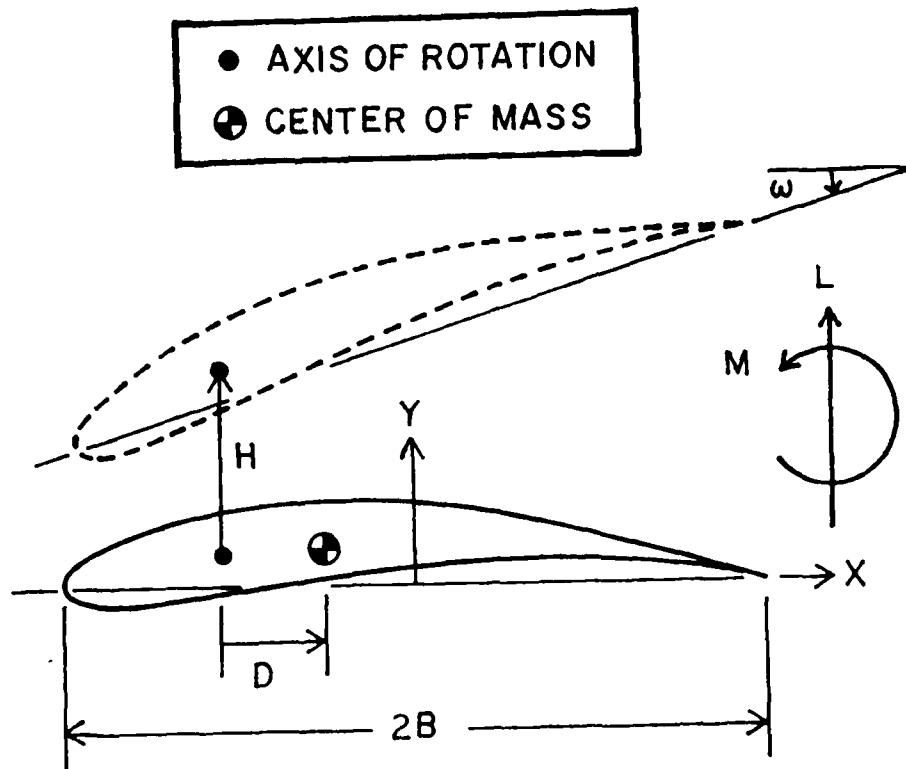
Figure 7.   Schematic of a Blade Section in Combined Bending and Torsional Oscillations.
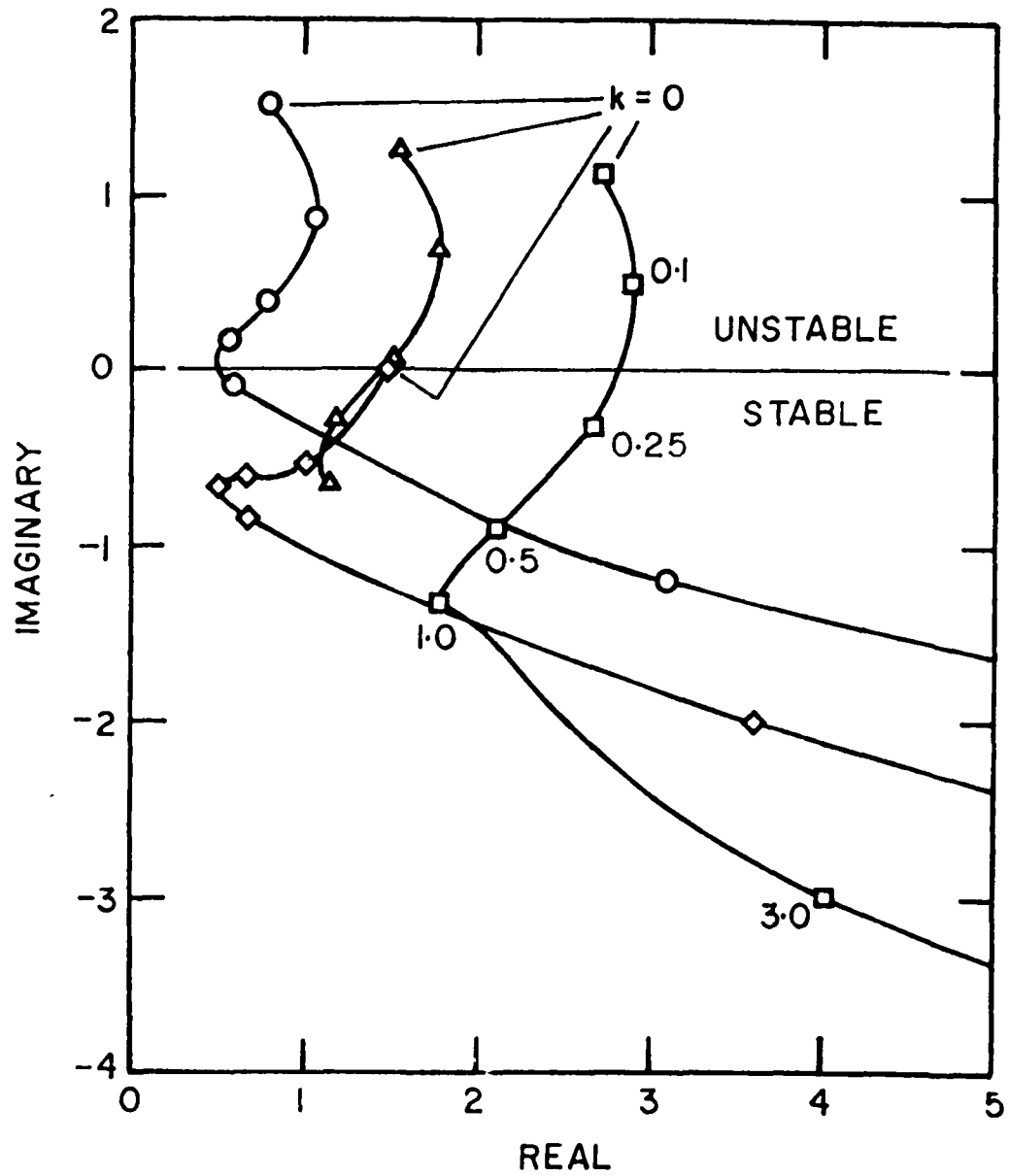
Figure 8.   Unsteady moments for a rotational motion. The reduced
frequency is varied from 0 to 3, compressor, ○; turbine, ☐;
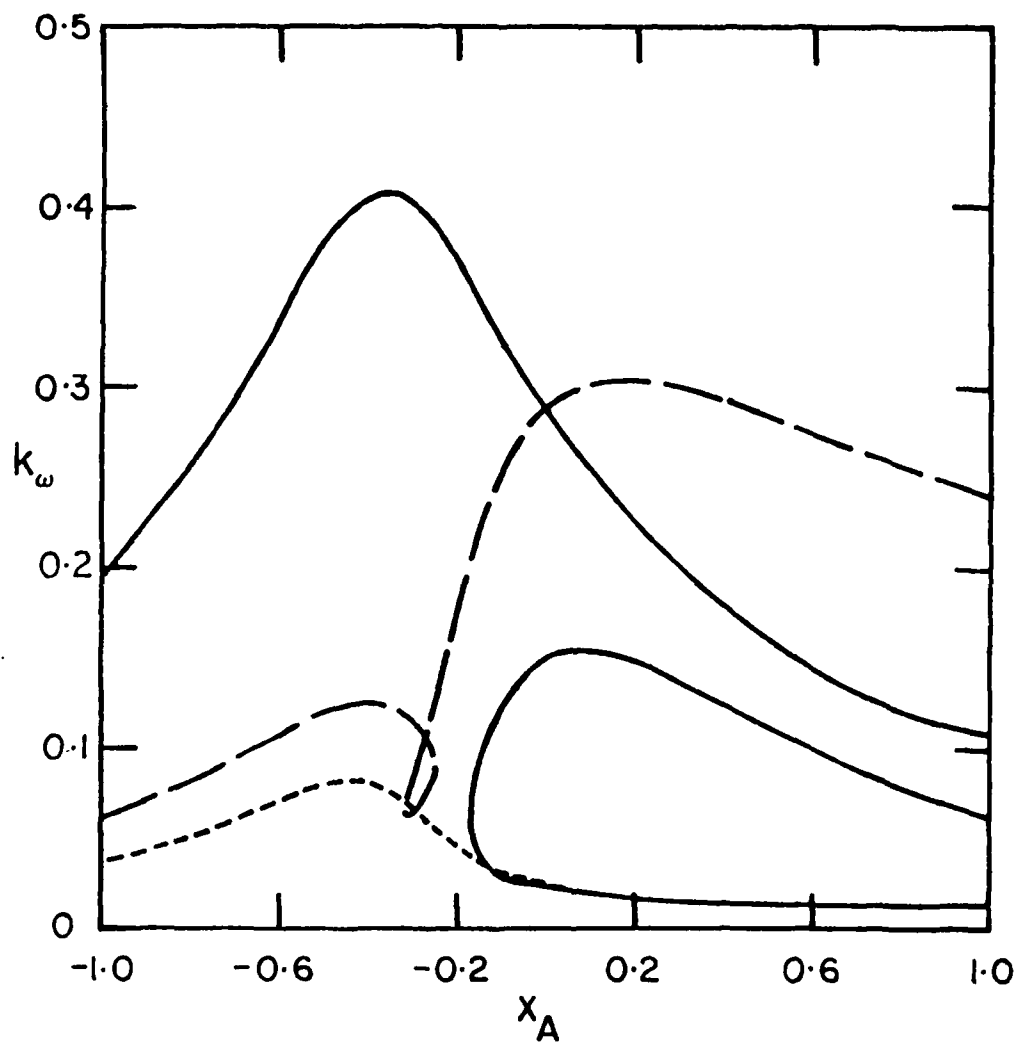single airfoil, ◇; flat plate cascade, △.

Figure 9.   Flutter boundary for K = 0.5. compressor, —; turbine,— —; single airfoil, ---.

Y

28.71°

CAMBER LINE

U_∞

28.71°

C.M.

0

$-\dfrac{C}{2}$

$\dfrac{C}{2}$

X
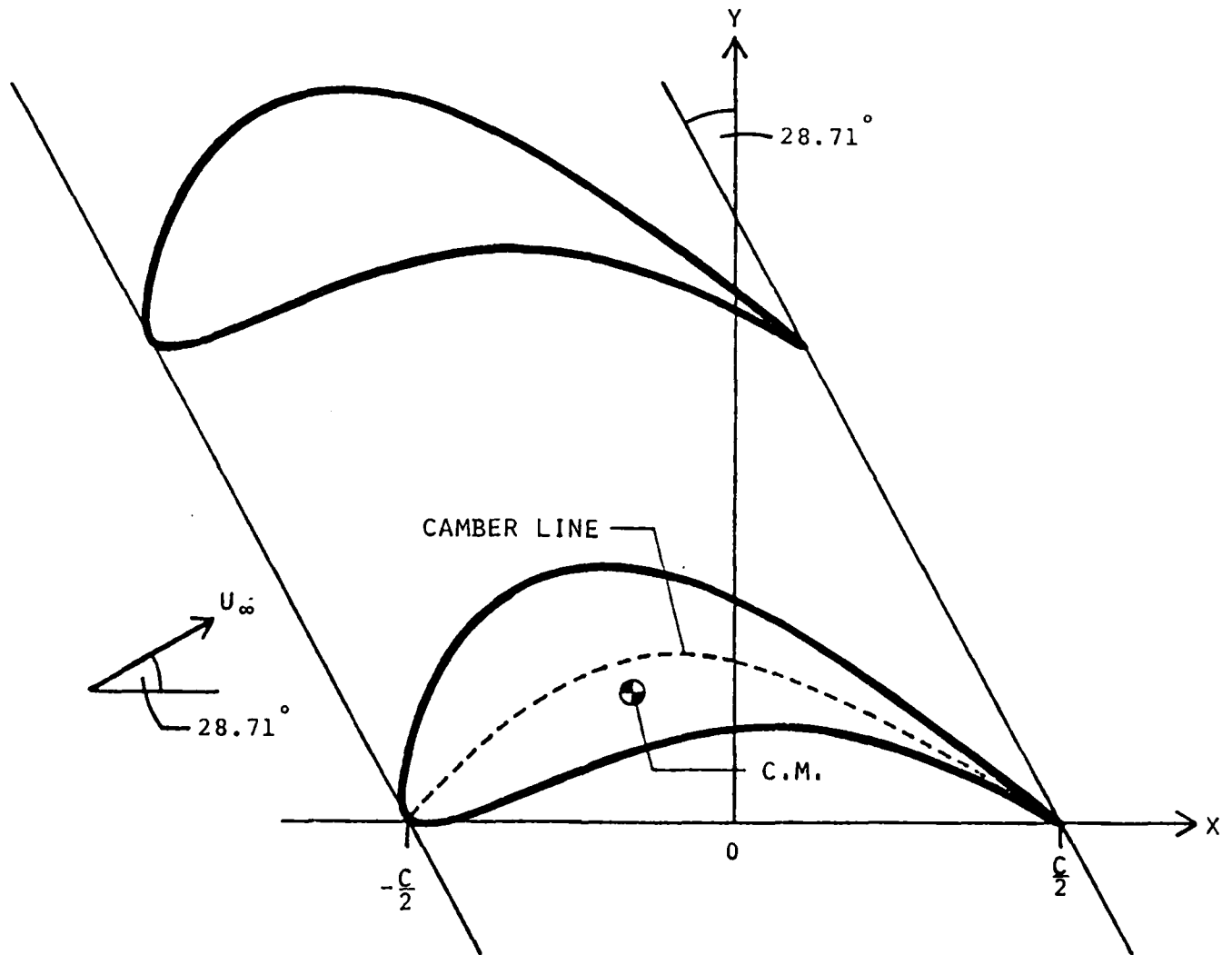
Figure 10.   The Brown Boveri Turbine Cascade.

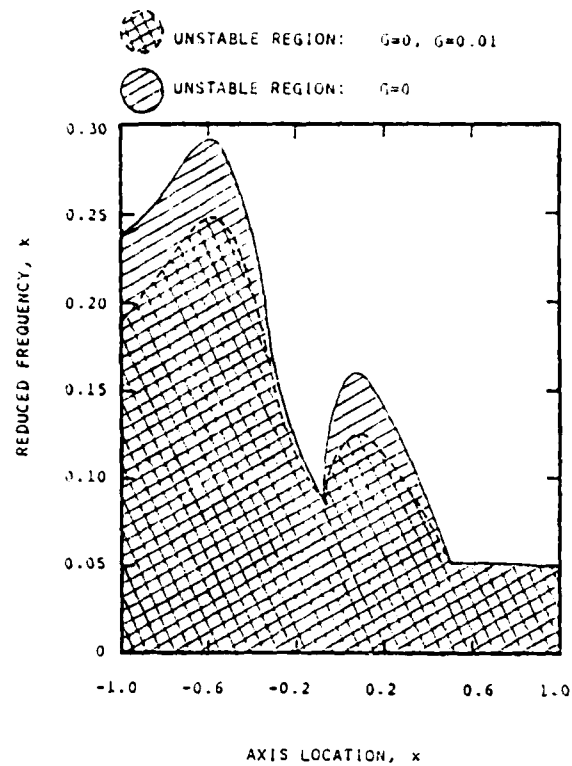Fig. 11. Stability Boundary for Coupled Bending and
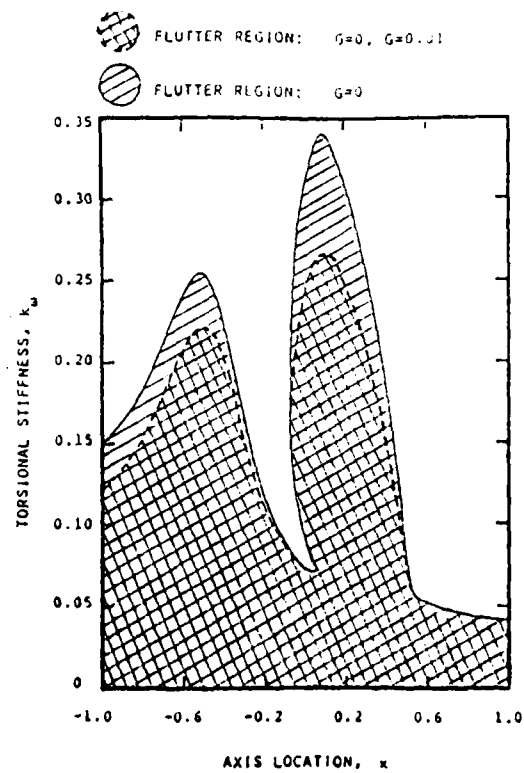Torsion with K=0.5 and σ=270 Degrees.

Fig. 12. Flutter Boundary for Coupled Bending and
Torsion with K=0.5 and σ=270 Degrees.

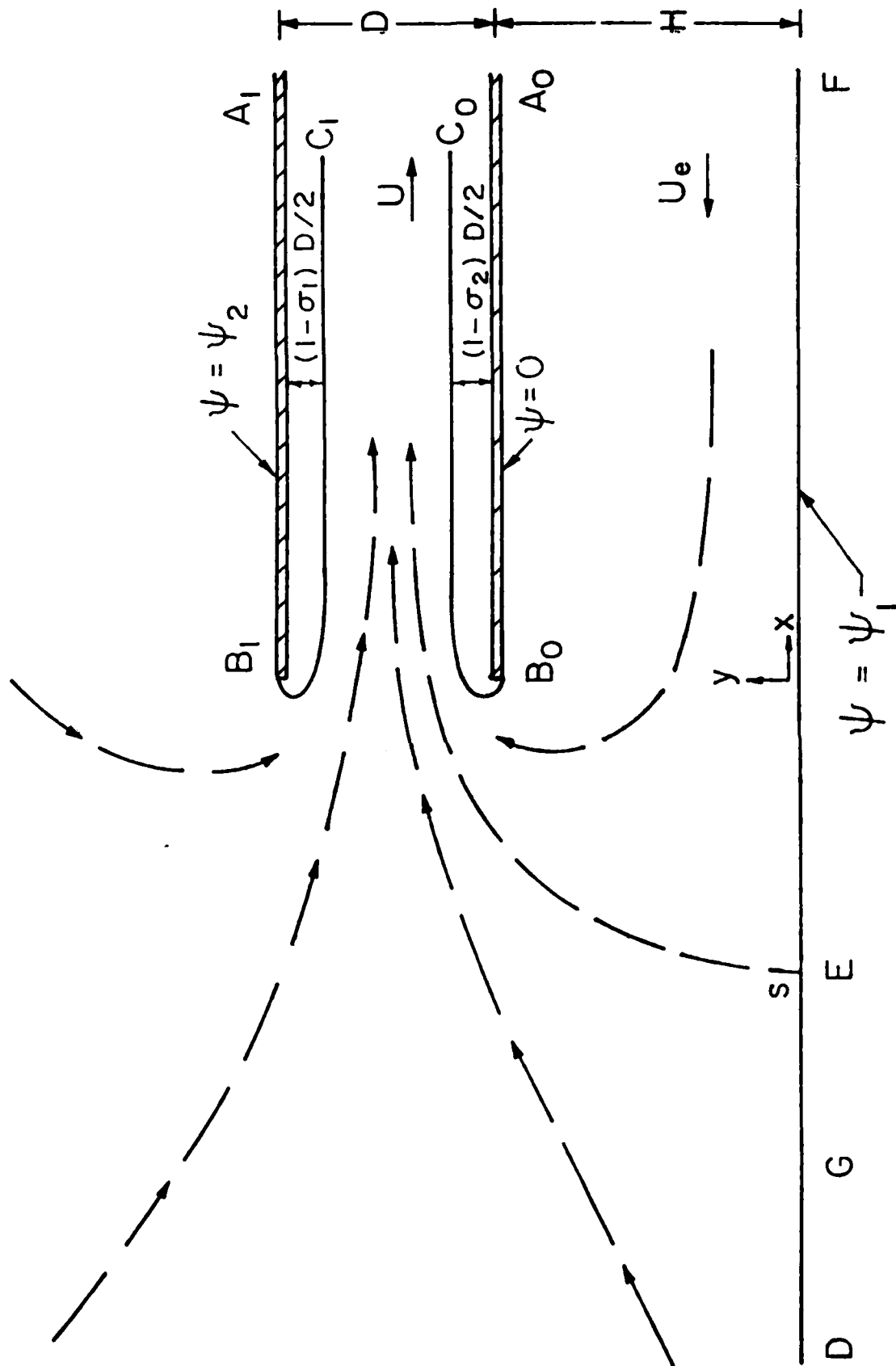Figure 13. Photograph of a Ground-Induced Vortex Entering Engine Inlet.
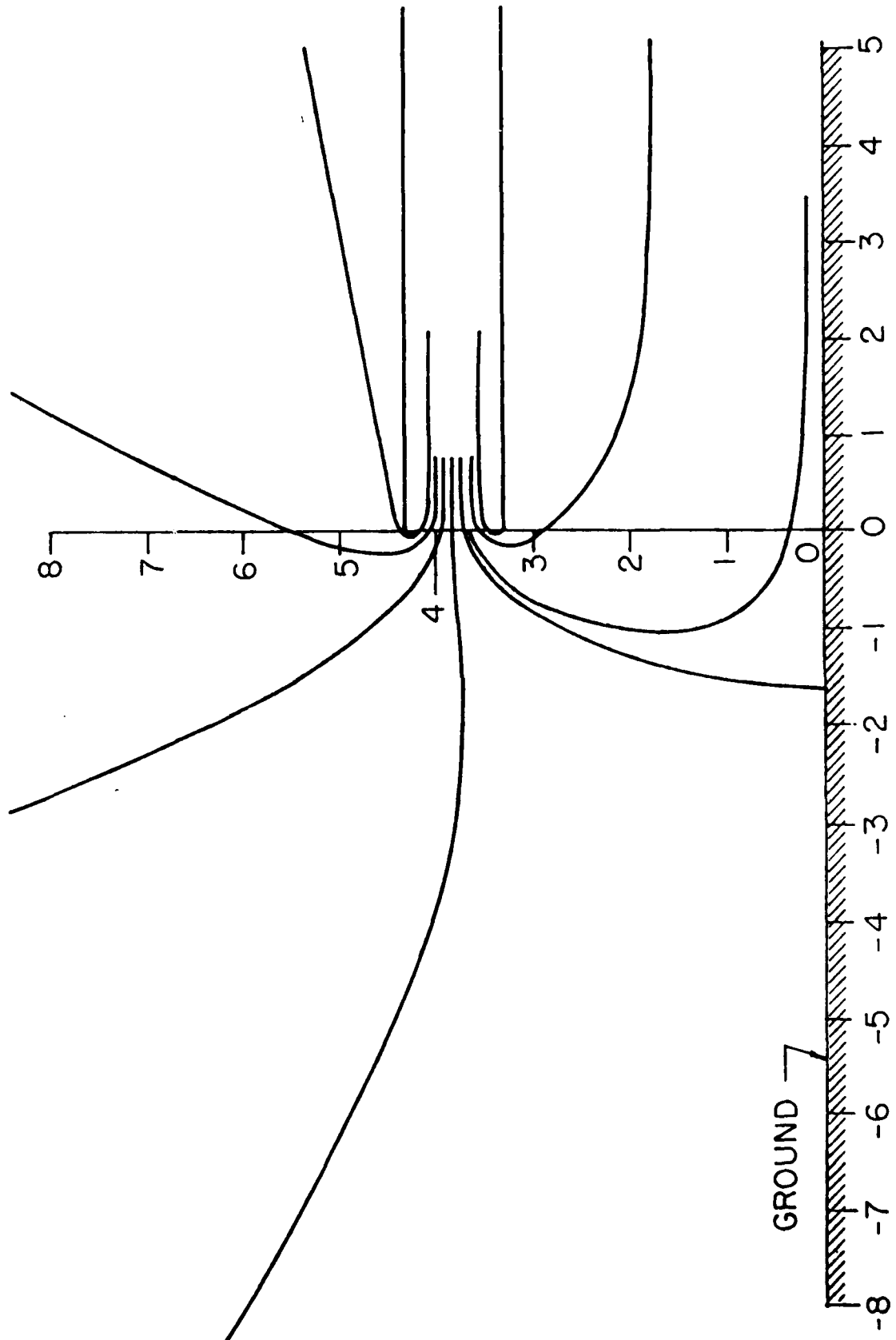
Figure 14. Schematic of Inlet Flow Near Ground
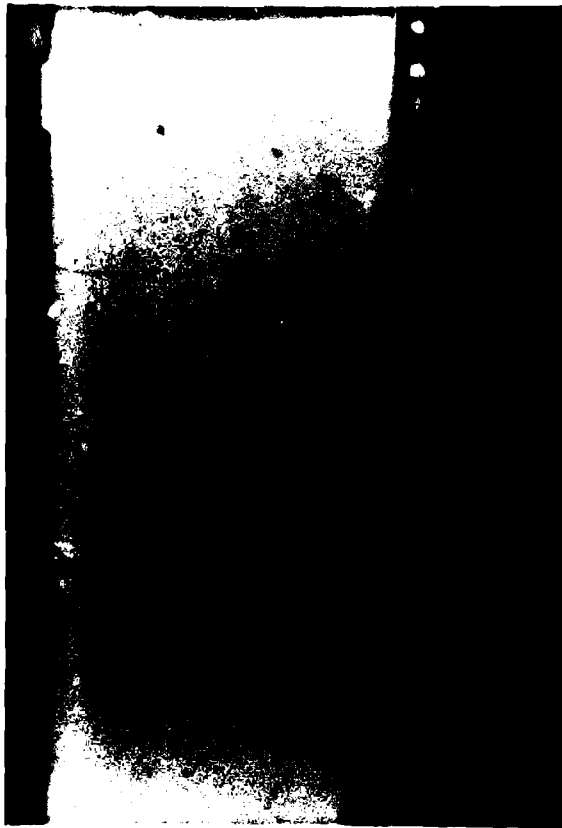
Figure 15. Streamline Pattern of Model Flow.

Figure 16. Photograph of Flow Pattern in the Water Table
Experiment for α = 0.3.

Figure 17. Photograph of Flow Pattern in the Water Table
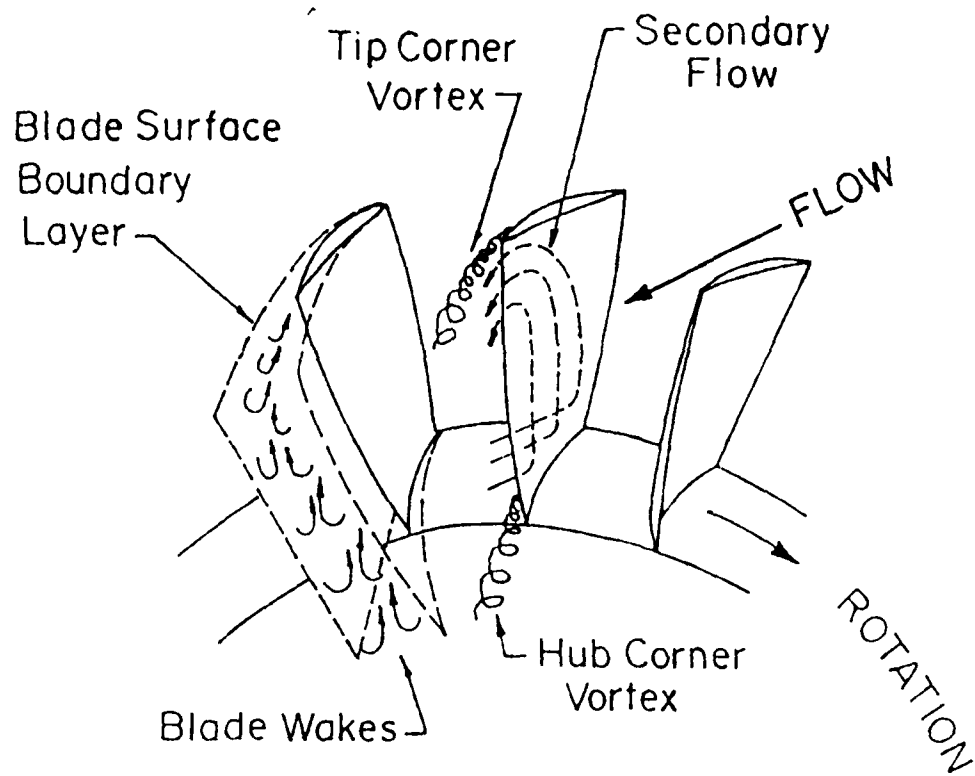Experiment Exhibiting Recirculating Flows for
$\alpha = 2$.

Figure 18.   SCHEMATIC REPRESENTATION OF FLOW BEHIND A ROTOR BLADE ROW

Figure 19. Airfoil Subject to 3D-Gust

VII. PUBLICATIONS RESULTING FROM OUR WORK UNDER AFOSR SPONSORSHIP

All publications listed below are authorized by Professor H. Atassi.
Only co-authors are listed.

1. "Interaction of a Small 3-D Gust Disturbance with an Airfoil", Bulletin of the American Physical Society, Vol. 24, No. 8, October 1979, p. 1127.

2. "Ground Effect on a Borda Mouthpiece Flow", Bulletin of the American Physical Society, Vol. 24, No. 8, October 1979, p. 1136. Co-author W.H. Newman.

3. "Unsteady Flow Past an Airfoil with Thickness Subject to a Two-Dimensional Gust", Bulletin of the American Physical Society, Vol. 24, No. 28, October, 1979, p. 1127. Co-author G. Hamad.

4. "A Two-Dimensional Potential Flow Model for Ground-Induced Effects and Jet and Fan Inlets", AIAA Paper No. 80-388, January 1980.

5. "Aerodynamic and Aeroelastic Characteristics of Oscillating Loaded Cascades at Low Mach Number. Part I: Pressure Distribution, Forces and Moments", Journal of Engineering for Power, Vol. 102, April 1980, pp. 344-351. Co-author T. J. Akai.

6. "Aerodynamic and Aeroelastic Characteristics of Oscillating Loaded Cascades at Low Mach Number. Part II: Stability and Flutter Boundaries" Journal of Engineering for Power. Vol. 102, April 1980, pp. 351-356. Co-author T. J. Akai.

7. "Three-Dimensional Periodic Disturbances Acting Upon Airfoils in Cascade", Presented at IUTAM Sumposium on Aeroelasticity in Turbomachines Lausanne, Switzerland, September 12-18, 1980. Also presented at joint NASA-Air Force Navy Symposium on Aeroelasticity of Turbine Engines, Part 39, pp. 1-7, NASA Lewis Research Center, October 27-29, 1980, Cleveland, Ohio.

8. "Stability and Flutter Analysis of Turbine Blades at Low Speed", Presented at IUTAM Symposium on Aeroelasticity in Turbomachines", Lausanne, Switzerland, September 8-12, 1980. Co-author T.J. Akai. Also presented at Joint NASA - Air Force - Navy Symposium on Aeroelasticity of Turbine Engines, Part 6, pp. 1-7, NASA Lewis Research Center, October 27-29, 1980, Cleveland, Ohio.

9. "Effect of Shape and Incidence on the Instability of an Airfoil in Pitching Oscillations", AIAA Paper No. 79-771, 20th Structural Dynamics and Materials Conference, April 4-6, 1979, St. Louis, MO. Co-authors .D.J. Gleason, and R.J. Dieckelman.

VIII. <u>INVITED LECTURES</u>

These are lectures given by Dr. Atassi on topics related to AFOSR
Contract No. F49620-79-C-0014.

"Unsteady Airfoil Theory and Its Application to Flutter Analysis",
University of Missouri, April 2, 1979, Rolla, Missouri.

"Flutter and Stability Analysis of Loaded Turbomachine Blades", Detroit
Diesel Allison, Division of General Motors, July 31, 1979, Indianapolis,
Indiana.

"Unsteady Aerodynamics: Early and Recent Developments", University of
Arizona, January 24, 1980, Tucson, Arizona.

"Interaction of Three-Dimensional Disturbances with Lifting Airfoils",
Office National d'Etudes et de Recherches Aerospatiapes, September 1,
1980, Paris, France.

"Stability and Flutter Analysis of Turbine Blades at Low Speed",
University of Paris, September 2, 1980, ORSAY, France.

"Stability and Flutter Analysis of Turbine Blades at Low Speed", von
Karman Institute for Fluid Dynamics, September 4, 1980, Brussels,
Belgium.

"Stability and Flutter Analysis of Turbine Blades at Low Speed",
University of Aachen, September 5, 1980, Aachen, Germany.

"European and Japanese Programs in Aeroelasticity in Turbomachines",
Joint NASA, Air Force, and Navy Conference on Aeroelasticity of Turbine
Engines, October 7-29, 1980, NASA Lewis Research Center, Cleveland, Ohio.

IX. THESES

William H. Newman: "A Two-Dimensional Potential Flow Model
for Ground-Induced Effects on Jet and Fan Inlets", M.S. Thesis,
May 1979, University of Notre Dame.

Dartzi Pan: "Flutter Analysis of a Two-Dimensional Turbine
Cascade at Low Mach Number", M.S. Thesis, August 1979,
University of Notre Dame.

X. AWARDS

William H. Newman: First Place Award in the AIAA Midwest
Student Paper Competition, Graduate Division, University of
Michigan, Ann Arbor, Michigan, March 1979.

Title of Paper: "Potential Flow Model for Ground Induced
Effects on Jet and Fan Inlets".

XII. PERSONNEL

All people who worked under the subject contract are listed below:

Hafiz Atassi, Professor and Principal Investigator
Robert Dieckelman, Research Assistant, (Partial Support)
Terrence J. Akai, Research Associate
Young-Nam Kim,   Research Associate
Dartzi Pan,   Research Assistant (Partial Support)
William H. Newman, Research Assistant (Partial Support)